Technology for generating clean energy by controlling the polarization of ferroelectrics to increase the power and energy density of electric vehicle drives

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Abstract: This article discusses a device developed using ferroelectric ceramics for power generation. The use of an electrochemical generator in the device improves power generation efficiency by controlling the polarization of the ferroelectric ceramics. Polarization control is based on a mathematical model. For every joule of electricity consumed, 3.5–5 joules of electricity are generated using mechanical energy, and even more with more efficient materials. The power plant's efficiency can reach 60–65 percent, depending on the ceramic modification and electrical circuit

Key-words: batteries, ceramics, electric vehicle, frequency, voltage, generator, charging time.

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1. Introduction

Finding a balance between scientific and technological progress and nature is crucial today. Therefore, developing electric vehicles as a means of transportation and reducing the cost of hydrogen production are potential solutions to serious environmental problems. The most practical are electric motorcycles, electric scooters, electric bicycles, electric forklifts, and other light vehicles. Light vehicles are typically equipped with batteries with a capacity of up to 10 kilowatt-hours and have a range of tens of kilometers. Electric vehicles can have batteries with a capacity of up to 100 kilowatt-hours and a range of hundreds of kilometers. A traditional electric drive system includes a power source (one or more batteries), a motor controller, the electric motor itself, and a mechanism (in some cases, absent) for transmitting motion to the drive element. Batteries have a low energy content and provide a short range for an electric vehicle on a single charge. Their weight and size also make storage difficult. These problems are apparently easily solved by so-called primary energy sources, which generate energy directly from fuels such as oxygen or hydrogen. Despite their high efficiency (approximately 60 percent), fuel cells have very specific drawbacks: the inability to recover energy during braking, low power density with high energy density, etc. Therefore, fuel cells for vehicles are very heavy. As a result, propulsion systems with drive motors based on them are inefficient.

2. Description of the design and physical processes of the proposed electric drive. Dependence of mass change on electric drive power

Taking into account the foregoing, an environment friendly unit of alternative technology with the use of electro-chemical generator (ECG), based on ferro-piezoelectric ceramics, is proposed. Such a power plant is characterized with both a high specific output and energy.

Theoretical and experimental research [1-4] prove, that a unit based on ferroelectrics, artificial ferro-piezoelectric ceramics is applied, can be used as the most efficient alternative to devices and technologies, used today for electric drive by foreign companies.

Experimental dependence [3], gained on small-sized full-cycle element (ø 2,3×1 mm) made of PZT (lead zirconatetitanate), proves the possibility of current I generation, equal to 4,5 mA, caused by a fluctuating mechanical force F, equal to 15 H, Figure 1.

The PZT film composition is solid solutions of PbZrO3 and PbTiO3. Electromechanical parameters (piezoelectric modulus, electromechanical coupling coefficient, permittivity, etc.) reach their maximum at a specific composition of 52% PbZrO3 and 48% PbTiO3. Modification of this composition with oxides of various metals has led to the creation of various PZT mode materials (domestically produced ceramics PZT - 19, PZT - 21, PZT - 23, etc.). Figure 1 shows the dependence for PZT – 23. In order to increase the power density is necessary to consider mainly the modification of the solid solution, electrical circuit, mechanical strength and ferroelectric element configuration when the ratio of the warmth radiation surface to the element volume will be the maximum possible. Furthermore, select of electric-field vector direction and mechanical stress components are taken into account. Dimensions of an element's certain form depend on its mass, the mass depends on electric power.

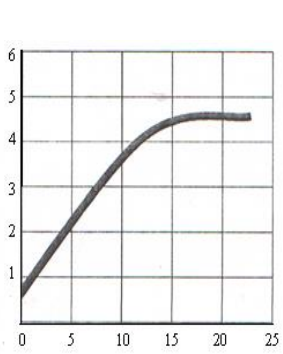


Fig. 2: Dependence of the current on mechanical load of a PZT system element.

Recalculation for a PZT unit of bigger sizes and the same mechanical stress goes well with calculations made, proving that the specific output and specific energy are enough for the run of a lightweight vehicle. Moreover, today there are multicomponent ferro-piezoelectric ceramics of a considerably higher electromechanical coupling factor K (a kind of efficiency factor of material's role in transformation of mechanical power into electric and vice versa) than a PZT system, expression (9). It also means that there are ways of generating bigger currents (bias currents in dielectrics) [4] describes experimental dependence of output voltage on mechanical load of ferro-piezoelectric ceramic elements of various modifications and closed circuits.

A system, allowing use less storage battery energy and improve the efficiency of transformation of mechanical power into electric, about by an order, due to electric characteristics of ferro-piezoelectric ceramics and physical-and-technical solutions (technologies), is required for efficient use of ferroelectrics. A created system, based on ferroelectrics, can transform up to 90 per cent of gained energy into net energy [5-7]. In brief, the idea of ECG operation, the main joint of the plant, includes a release of "frozen" energy of an oxidant chemical reaction and a ferro-piezoelectric ceramic element, a multicomponent system of a solid solution. This energy is generated by mechanical energy, ferroelectric second-kind transition, and interlayer and dipole polarization [5].

Structurally, ECG is a ferro-piezoelectric ceramic element of a certain size and form with metal contacts and attached leads for its engagement into electric circuit. Efficiency rate of the plant, subject to the use of mechanical energy, makes 60 … 65 percent.

High efficiency of generation electric power in the plant (efficiency of the polarization of ferroelectric increase) is possible due to modification of ferro-piezoelectric ceramics, electric circuit, conditions of mechanic load, and, it was aforesaid, interlayer and dipole polarization. The plant comprises also a power supply (a storage battery for e-vehicle), a device for mechanical energy generation and electromechanical transducer Figure 2. Energy consumption of 1 joule, using mechanical energy, makes it possible to get the output of 3, 5 … 5 joule of electric energy. Used mechanical energy is generated by a device of a simple construction.

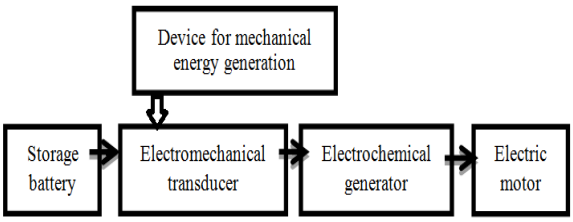


Fig. 2: Installation block diagram.

The possibility of increasing the efficiency of polarization control in ferroelectrics is explained by theoretical and experimental studies [4]. To describe

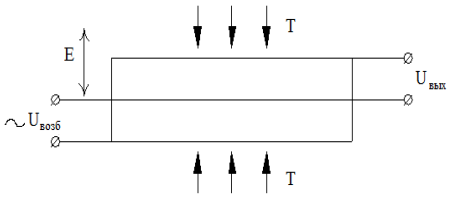
the polarization process, Figure 3 shows a schematic representation of an electromechanical transducer based on PZT ferroelectric ceramics [4]. The direction of the electric field vector E of the lower ferroelectric ceramic element and the direction of the mechanical stress component T (mechanical force F) of the upper one coincide. These processes are described by the equation of the piezoelectric effect.

$$P^E = d \cdot T + \varepsilon^T \cdot E,$$
$$S^T = d_t \cdot E + s^E \cdot T \quad (1)$$

Equations (1) for this case are:

$$P_i^E = d_{ij} T_j,$$
$$S_j^T = d_{ij} \cdot E_i \quad (2)$$

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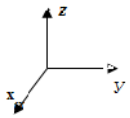


Fig. 3: Simplified diagram of an electromechanical converter

Upper indexes E and T go for constancy of electric field voltage and mechanical load, respectively.

First equation (2) goes for the run of ferroelectric piezoelectric ceramic element, excited by the strain. The second equation is true to the run of ferroelectric piezoelectric ceramic element, excited by the electric field.

Subject to the known matrix of piezoelectric modules, e.g. for a PZT material [8]

$$d_{ij} = \begin{Vmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{13} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{Vmatrix} \quad (3)$$

the equation for ferro-piezoelectric ceramic element, excited by the electric field, has a tensor form after transformation:

$$S_1 = d_{31} \cdot E_1$$
$$S_2 = d_{32} \cdot E_3$$
$$S_3 = d_{33} \cdot E_3$$
$$S_4 = d_{24} \cdot E_2 \quad (4)$$
$$S_5 = d_{15} \cdot E_1$$
$$S_6 = 0$$

Equation for ferro-piezoelectric ceramic element, excited by the mechanical stress, after transformation is following:

$$P_1 = d_{15} \cdot T_5$$
$$P_2 = d_{15} \cdot T_4$$
$$P_3 = d_{31} \cdot T_1 + d_{31} \cdot T_2 + d_{33} \cdot T_3 \quad (5)$$

Analysis of the equations (3), (4) and (5) makes it clear, that excitement of deformation of one ferro-piezoelectric ceramic element along the axes Z is required, i.e. S_3, excited only by the electric field vector E_3 (4) for S_3, as far a correspondent mechanical stress component is concerned, e.g. T_3 true to the axes Z. The other ferro-piezoelectric ceramic element, fluctuating in the same direction under the influence of the strain component $\boldsymbol{T_3}$ and moving in the same direction as the electric field E_3, is characterized with the existence of a polarization vector P_3, (5) for P_3.

Active mechanical stress components T_1 and T_2 also cause polarization in ferro-piezoelectric ceramic element and, consequently, charges. However, these charges are not effective because of the static mode of this element's work in T_1 and T_2 directions. Dynamic mode of ferro-piezoelectric ceramic element's work is achieved in the direction of a mechanical stress component T_3.

Control for polarization of ferroelectrics is achieved due to the proper choice of vector of electric field's mechanical stress E, which coincides with the strain component *T* direction.

Moreover, the equations of transformation for the plant of this construction and ferro-piezoelectric

ceramics under active mechanical stress and closed output electrodes and E=0 is following:

$$S^E = s^E T$$
$$D^E = P^E = dT \quad (6)$$

S^E goes for deformation under field strength of, E=0; s^E is compliance under E=0; D goes for displacement when E=0; P means polarization when E=0.

The field with mechanical stress equal to E is used in case of open electrodes and the lack of strain (T=0), when the element can be easily deformed. The equation is following:

$$S^T = dE$$
$$D^T = \varepsilon_a^T E \quad (7)$$

S^T means deformation under T=0, different from S^E, D^T *also* differs from D^E. If then decided that the electrodes are open and the field strain *E* and mechanical stress *T* influence simultaneously, and displacement D=0, then an interdependence between E and *T* can be found:

$$T = -\frac{\varepsilon_a^T}{d} E, \quad \text{or}$$
$$S^D = \left(S^E - \frac{d^2}{\varepsilon_a^T}\right) T = s^D T$$

Where D is less than S^E. It is clear that electric field E can be applied for changing elastic compliance s of ferroelectrics, i.e. for control of its rigidity (compressibility).

If *E*and Tinfluences imultaneously, and deformation S=0, i.e. the element is pressed and does not deform, then an interdependence between mechanical stress T and electric field strain E is observed:

$$T = -\frac{d}{S^E} E$$

Displacement D is found by the expression [8]:

$$D^T = \left(\varepsilon_a^T - \frac{d^2}{S^E}\right) E = \varepsilon_a^T \quad (8)$$

Absolute dielectric constants of the pressed element ε_a^S is obviously less than ε_a^T (7) and they are described in equation (9), K is an electromechanical coupling factor:

$$\varepsilon_a^S = \varepsilon_a^T \left(1 - \frac{d^2}{\varepsilon_a^T S^E}\right) = \varepsilon_a^T (1 - K^2) \quad (9)$$

s^E goes for electric field strain compliance E=0
ε_a^T is an absolute dielectric constant under mechanical stress T=0.

Thus, control of compressibility and electric elasticity of ferro-piezoelectric ceramic elements in the plant allows to increase sensitivity of the output electric voltage of these elements to the acting mechanical load [4, 9]. The function of ECG transformation in the plant is following:

$$U_{вых} = K_H \frac{d_{ij} \cdot F}{C_{эхг} + C_H} \quad (10)$$

$U_{вых}$ means an output electric voltage of ECG, *F* is acting mechanical force, $C_{эхг}$ goes electro capacity of ECG, $C_н$ is electrical load capacity (load electrical devices), $K_н$– an electrical voltage increase rate due to control of polarization of ferroelectrics, d_{ij} –piezoelectric module, induced polarization per unit of mechanical stress [10-13].

Equation (9) proves that the electromechanical coupling coefficient K depends on the ratio of the permittivity of loaded and free ferroelectrics, i.e., the change in dielectric capacitance under mechanical loading. In the case of K = 0.5 (the average value), the ratio is 0.75. This, in turn, is very important for the output electrical voltage (power density) of the setup (10); moreover, K of modern ferro-piezoelectric ceramics is 0.6...0.7 (ε_a^S differs significantly from ε_a^T, since the permittivity and electrical capacitance are directly proportional). Tests have shown that a twofold increase (decrease) in the electrical load power (P_n) causes a twofold (2) increase (decrease) in the mass of the ECG (M_{ecg}) by 2√ (2), a threefold increase (decrease) by 3√3, and so on. The mass of the mechanical converter, together with the mass of the mechanical energy generating device (Fig. 2), is 10–15 percent greater than M_{ecg} and also depends on P_n as well.

Figure 4 shows a M_{ecg} - Pn growth-increase diagram. The above and the diagram allow us to calculate the mass of the plant (excluding the battery and actuator) taking Pn into account. The diagram shows a point where P_n = 0.182 kilowatts and M_{ecg} = 0.83 kg, around which P_n and M_{ecg} vary almost directly proportionally. M_{ecg} grows more slowly below this point and more rapidly above it.

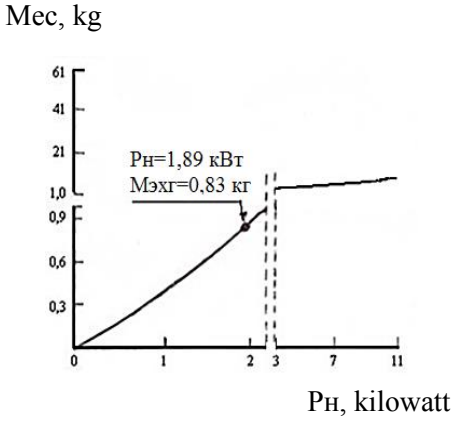


Fig. 4: $M_{ec,\,kg}$ - $P_н$ growth-increase diagram.

As foresaid, 1 joule energy consumption from the storage battery gives an electric power output of 3,5 …. 5 joule under mechanical stress.

As 4 joule of energy is generated per 1 joule of storage battery energy, required for the run of the plant, 4 times energy increase in comparison with the energy, lost by the storage battery, is generated, not taking into account the loss of battery. It means that an e-vehicle run charged from one battery is also 4 times longer (an average value) in comparison with the traditional electric drive. The increase of the plant's mass is insignificant.

Thus, an alternative electric drive has certain advantages to a traditional one. Providing a certain level of ferroelectric devices leakage current is required for working in statics and with step electrical voltage change. For example, when objects are precisely moved with the help of actuators having a static leakage current not more than 5 μA. Ferroelectric high electrical resistance reduces the leakage current up to μA units or less. The leakage current can slightly increase, due to improper operation of devices (usually - it's unacceptable temperatures, humidity and electrical voltage), as it causes the activation of electrode material migration into ceramics. In practice, maintaining dynamic conditions (as in energy for heat and partial charge of the storage the proposed setup) and proper operation it can be neglected. Especially at low electrical voltage and low mechanical stress.

Certain obstacles also arise, related to the importance of uniformly distributing high mechanical loads on fragile ferro-piezoelectric ceramic elements [14, 15-17] and the initial polarization of larger elements for higher power generation, as well as the lack of research funding. The use of modern methods helps to overcome the obstacles easily.

The plant proposed can also be used as an environment friendly source of electric power, reserved and autonomous (charging from a battery or a power unit). It is important to highlight, that the plant mass is of no importance, as in case of an electric drive, as emergency sources of energy are permanent.

3. Brief description of the operating principle of the ECG

The main technical unit of the power plant's is the ECG, whose operating principle is based on the release of "frozen" energy from a chemical reaction between an oxidizer and a ferroelectric ceramic element of a multicomponent solid solution system. This energy depends on the mechanical load, the second-order ferroelectric transition, and the interlayer and dipole polarization in a specific frequency and temperature range [14]. The increase in energy density occurs in two stages: in the first stage, the polarization of the ferroelectric increases, and in the second, the electrical voltage at the ECG output increases, and, consequently, the power converted into energy [13, 14].

Figure 5 shows the nature of the change in the electromechanical transducer electrical voltage at frequencies below resonance, where the generator resistance can be considered purely capacitive [5].

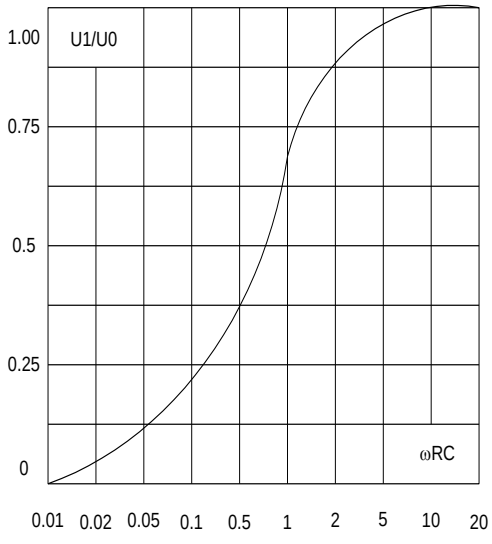


Fig. 5: Frequency response of an electromechanical transducer.

U_O is the amplitude of the voltage appearing at the converter output, the open-circuit voltage.

U_1 is a voltage that changes depending on the connected electrical resistance, i.e. the load

The experimental curve in Figure 5 reflects the dependence of voltage U_1 on frequency w and electrical load R of an electromechanical transducer made of ferroelectric PZT-19 material, measuring ø 10 x 1 mm, under a mechanical load of 2.5 MPa (see [4], Fig. 4.1, curve 2). Depending on the nature of the transducer's electrical load (reactive or active), the connection diagram and power consumption vary [4, 5].

This reduced-size electromechanical transducer is used to explain the operation of an electrochemical generator.

4. Conclusion

The proposed alternative innovative technology for generating additional energy offers advantages over solar and wind technologies: it is independent of climatic conditions and time of day, and is highly efficient. The efficiency of converting mechanical energy into electrical voltage increases by approximately an order of magnitude due to the electrophysical properties of ferroelectrics and physical engineering solutions (technologies). The technology utilizes engineering and physical solutions (innovations). The technical details of these innovations have not yet been disclosed, as work is underway to improve the technology. The main components of the ECG are protected by copyright and patents, and their effectiveness has been confirmed by experimental studies [4, 5]. The combination of physical, chemical, and engineering processes in ferroelectrics increases the energy extracted from batteries (or other energy sources). This increase is explained by a simple fact: the rate of increase in output voltage exceeds the rate of increase in output electrical resistance.

Figure 5 shows that U_1, i.e., the output voltage of the ECG in a given frequency range, is several times higher than its output resistance R. The use of highly efficient four-component ferroelectrics further increases this excess. As a result, the ECG produces approximately 6-8 times more energy than it consumes. This excess energy can be used to increase the driving range and reduce charging time—two factors hindering the adoption of electric vehicles. For example, the driving range could be increased by 2.5 times, to approximately 600-800 km, and the charging time could be reduced by 3.5 times, to approximately 9-12 minutes. This includes fast charging for 30-40 minutes. As a result, consumer demand can be fully met.

The energy unit is easy to manufacture, does not require rare earth elements, and can also be used, for example, to save energy when powering various energy-intensive devices [20]. Further research is aimed at studying the effectiveness of using ferroelectrics in hydrogen technologies, as well as increasing the energy capacity of batteries used to extend the autonomous operation of electric vehicles.

Thus, the control of the degree of ferroelectric polarization for generating additional energy is primarily determined by:

- modification of ferroelectrics and the electrical connection scheme;
- mechanical loading (design features of ferroelectric devices);
- interlayer or dipole polarization of ferroelectrics within the operating temperature range, as well as frequencies in the range of approximately 1 ... 1.5 (10^3 - 10^5) Hz.

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